



# A common-path, multi-channel heterodyne laser interferometer for sub-nanometer surface metrology

Feng Zhao, Jennifer E. Logan, Stuart Shaklan, and Michael Shao

Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grove Drive, Pasadena, California 91109, U.S.A.

neterodyne interferometry metrology nanotechnology





## Objective

- To measure thermal stability of telescopes and other optical subsystems;
  - measurement of changes in surface figure (wavefront) at subnanometer level (~100pm or better).

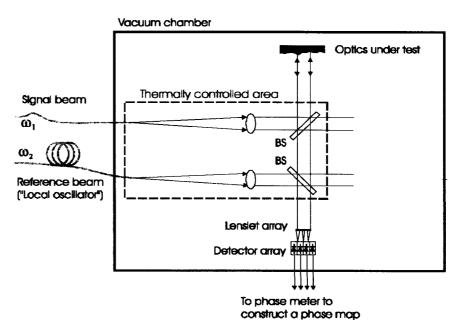
June 18, 1999





## Enabling Technology: COmmon-Path Heterodyne Interferometer (COPHI)

- Measure the heterodyne signal phase between sub-apertures using a 2-D detector array;
- Construct a 2-D phase map (relative surface height);
- Heterodyne detection ensures picometer level measurement.



June 18, 1999





## Features of COPHI

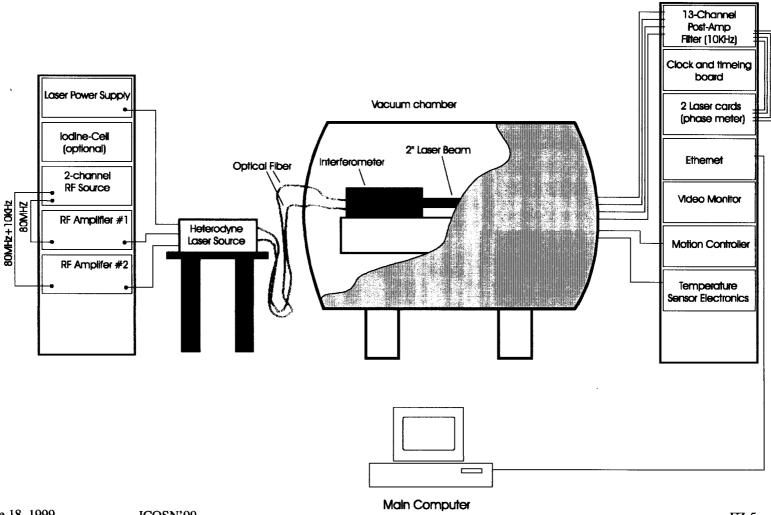
- Common-path reduces:
  - fringe phase error due to laser frequency and power fluctuations;
  - optical path length error caused by structural vibrations (piston mode).
- Wide applications:
  - thermal deformations of optics;
  - beam walk (single mirror, compressor, delay line, etc.);
  - corner cube articulation error;
  - on-board wavefront monitoring, etc.

June 18, 1999





## Instrument Schematic



June 18, 1999

ICOSN'99

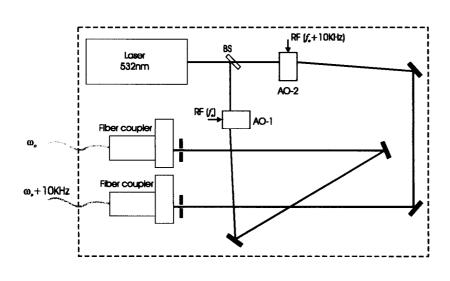
FZ-5





## Heterodyne Laser Source

- Because reference and unknown signals are common mode, laser frequency noise and intensity fluctuations are cancelled.
- Two PM fiber pigtailed output;
- 10KHz heterodyne frequency;
- Heterodyne frequency stability: 1ppm/hr;
- 1:4 power ratio (8mW:30mW);
- $\lambda = 532$ nm.

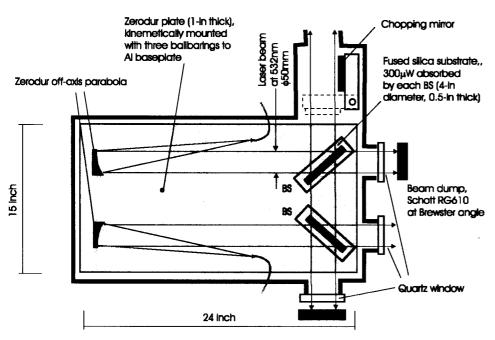








#### Athermalization of Key Optical Components

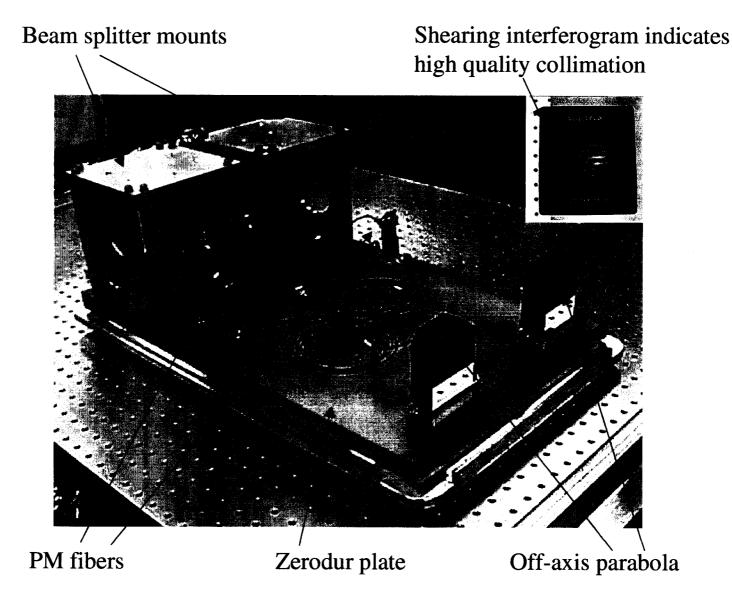


- Use low CTE material such as Zerodur off-axis parabolic reflector to reduce wavefront distortion;
- Zerodur base plate to reduce defocusing error;
- Compromise reflection distortion (CTE only) with transmission distortion (both CTE and dn/dT) in selecting substrate material for the two beam splitters;
- Super-Invar micrometer screws on BS mount to maintain pointing stability;
- De-couple radiation from others by:
  - aluminize chopping mirror and parabolic mirrors;
  - quartz window (IR opaque)



#### **COPHI Collimator Assembly**



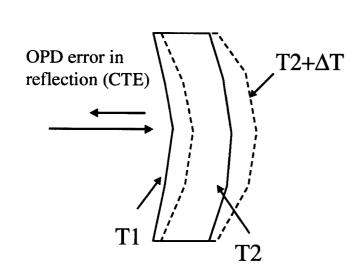




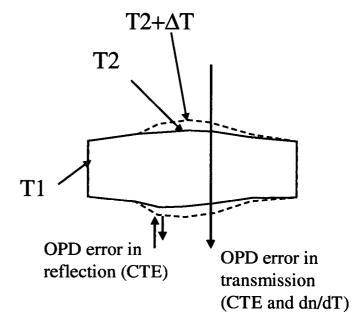


#### What We Care About Is the CHANGE in Temp Gradient

- Change is much smaller than static temp gradient;
- A simplified model to estimate the required temp gradient stability;
  - Front-back (axial) temp gradient stability;
  - Center-edge (radial) temp gradient stability.



Front-back (axial) temp gradient changes



Center-edge (radial) temp gradient changes





## Reduce Thermal Stability Requirement by Periodic Referencing

- Use a stable reference mirror ("chopping mirror") to periodically calibrate the wavefront error in the interferometer setup;
- Reduce the thermal stability requirement from 0.x mK/hr to 0.x mK/a few min;
- Positioning repeatability:
  - $-1 \mu m$ , linear;
  - $-1 \mu rad$ , angular;

June 18, 1999 ICOSN'99 FZ-10





#### Derived Temp Stability Requirement of Key Optical Components

Temp gradient stability (front-back)         1.600         (2pm)         0.080         (2pm)         1.778         (1pm)           Temp gradient stability (radial)         1.600         (1pm)         0.015         (2pm)         8.000         (1pm)		Parabolic mirror	(Zerodur-2)	Beam splitter (	fused silica)	Chopping mirror (Z	erodur-0)
Temp gradient stability (radial)  1.600  (1pm)  0.015  (2pm)  8.000  (1pm)  Notes: (1) Operating temperature range 15-35 deg C;  (2) All temperature units are in milli Kelvin (mK);  (3) Stability refers to 5 minutes time period;  (4) Both parabolic mirrors are aluminized;  (5) Chopping mirror dimension: 3-inch diameter, 0.5-in thick. Substrate material: Zerodur expansion class-0;  (6) Chopping mirror is aluminized;  (7) Beam splitter substrate material: fused silica; coating: 50/50 dielectric on one surface, and AR dielectric on other surface;  (8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%;  (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical element;  (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element;  (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	Bulk temperature stability	16.000	(2pm)	None		None	
Notes: (1) Operating temperature range 15-35 deg C;  (2) All temperature units are in mili Kelvin (mK);  (3) Stability refers to 5 minutes time period;  (4) Both parabolic mirrors are aluminized;  (5) Chopping mirror dimension: 3-inch diameter, 0.5-in thick. Substrate material: Zerodur expansion class-0;  (6) Chopping mirror is aluminized;  (7) Beam splitter substrate material: fused silica; coating: 50/50 dielectric on one surface, and AR dielectric on other surface;  (8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%;  (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical element;  (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element;  (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	Temp gradient stability (front-back)	1.600	(2pm)	0.080	(2pm)	1.778	(1pm)
(3) Stability refers to 5 minutes time period; (4) Both parabolic mirrors are aluminized; (5) Chopping mirror dimension: 3-inch diameter, 0.5-in thick. Substrate material: Zerodur expansion class-0; (6) Chopping mirror is aluminized; (7) Beam splitter substrate material: fused silica; coating: 50/50 dielectric on one surface, and AR dielectric on other surface; (8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%; (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical eleme (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	Temp gradient stability (radial)	1.600	(1pm)	0.015	(2pm)	8.000	(1pm)
(3) Stability refers to 5 minutes time period; (4) Both parabolic mirrors are aluminized; (5) Chopping mirror dimension: 3-inch diameter, 0.5-in thick. Substrate material: Zerodur expansion class-0; (6) Chopping mirror is aluminized; (7) Beam splitter substrate material: fused silica; coating: 50/50 dielectric on one surface, and AR dielectric on other surface; (8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%; (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical eleme (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	Notes: (1) Operating temperature range	ge 15-35 deg C;					
(4) Both parabolic mirrors are aluminized; (5) Chopping mirror dimension: 3-inch diameter, 0.5-in thick. Substrate material: Zerodur expansion class-0; (6) Chopping mirror is aluminized; (7) Beam splitter substrate material: fused silica; coating: 50/50 dielectric on one surface, and AR dielectric on other surface; (8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%; (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical eleme (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	(2) All temperature units are in	mili Kelvin (mK);					
(5) Chopping mirror dimension: 3-inch diameter, 0.5-in thick. Substrate material: Zerodur expansion class-0; (6) Chopping mirror is aluminized; (7) Beam splitter substrate material: fused silica; coating: 50/50 dielectric on one surface, and AR dielectric on other surface; (8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%; (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical elemet (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	(3) Stability refers to 5 minutes	time period;					
(6) Chopping mirror is aluminized; (7) Beam splitter substrate material: fused silica; coating: 50/50 dielectric on one surface, and AR dielectric on other surface; (8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%; (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical eleme (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	(4) Both parabolic mirrors are	aluminized;					
(7) Beam splitter substrate material: fused silica; coating: 50/50 dielectric on one surface, and AR dielectric on other surface; (8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%; (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical eleme (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	(5) Chopping mirror dimension	3-inch diameter, 0.5	-in thick. Su	bstrate material:	Zerodur expar	sion class-0;	
(8) Laser power dissipated in beam splitter: 0.3mW at BS1, and 0.01mW at BS2; (estimate by assuming 1% absoprtion)  Laser power fluctuation < 2%;  (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical eleme (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	(6) Chopping mirror is aluminiz	ed;					
Laser power fluctuation < 2%;  (9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical eleme (10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	(7) Beam splitter substrate ma	terial: fused silica; co	oating: 50/50	dielectric on on	e surface, and	AR dielectric on other	surface;
<ul> <li>(9) The front-back temperature requirement applies between any two points on the front and back surfaces of the optical eleme</li> <li>(10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element;</li> <li>(11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;</li> </ul>	(8) Laser power dissipated in t	eam splitter: 0.3mW	at BS1, and	d 0.01mW at BS	2; (estimate by	assuming 1% absop	tion)
(10) The radial temperature requirement applies between any two points across the central 50mm area of the optical element; (11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	Laser power fluctuation < 2	2%;					
(11) Prefer less than one week to reach this quasi-equalibrium condition after pump-down;	(9) The front-back temperature	requirement applies I	between any	, two points on th	ne front and ba	ck surfaces of the opt	ical element
	(10) The radial temperature rec	juirement applies bety	ween any tw	o points across	the central 50r	nm area of the optical	element;
(12) Temperature stability on other components: estimated 10mK.	(11) Prefer less than one week	to reach this quasi-e	qualibrium o	condition after pu	mp-down;		
	(12) Temperature stability on o	ther components: est	timated 10m	ıK.			
	waterinanderfelderfelderfelder (mit het film of med		AND THE PARTY OF T				

June 18, 1999



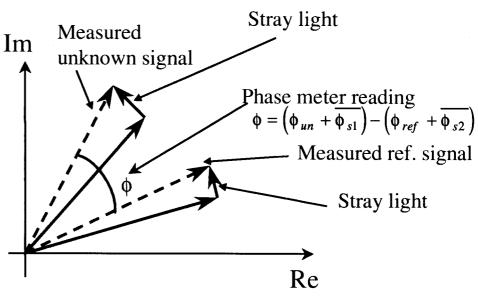


## Stray Light

- Coherent stray light will cause a phase error in the heterodyne signal;
- Only TIME-VARYING part of this phase error is important because COPHI is to measure surface deformations, i.e., changes in phase;

$$\frac{d\phi}{dt} = \frac{d}{dt} \left( \phi_{un} - \phi_{ref} \right) + \frac{d\overline{\phi_{s1}}}{dt} - \frac{d\overline{\phi_{s2}}}{dt}$$

- The contribution of stray light can be negligible if  $\phi_s$  is constant (including =0)
- Averaging reduces the error:
  - stray light incident angle;
  - detector area;
  - stray light wavefront quality;
  - dithering in time and integrate.







#### Stray Light Control in COPHI

- Reflection from back surface of the beam splitters:
  - 0.5 deg wedge;
  - -30dB reflection (AR coating), -30dB isolation using spatial filtering;
  - average ~100 fringes across 5mm aperture;
  - constant in phase ( $\Delta\theta$ <0.002 rad) because of thermal stabilization, and proportional in amplitude;
  - ~1pm
- Scattering from dust:
  - add a constant phase offset by "static dusts" (such as scratches on optics);
  - need clean environment to avoid "mobile" dusts;
  - not a concern in clean vacuum chamber
- Reflection from fiber tip:
  - APC connector (angle-polished, 16 deg) to launch fiber light;
  - reflected beam off by 32 deg, misses the parabola (f/5, 6 deg half angle);
  - not a concern;
- Reflection from detectors:
  - "spatially incoherent" (phase randomization) by using home-made "diffuser";
  - not a concern;
- Reflection imaging optics:
  - AR coating (v-type);
  - can tilt lens without losing imaging "quality" (our "camera" has only 10X10 pixels);
  - need to be careful in selecting lenses (curvatures) that don't send a reflection right into the detector.





## Effects of Vibration

- Insensitive to piston mode because of common path, a big plus;
- Tip/tilt modes ranging from 1Hz to 0.1Hz will cause an error in the constructed surface map:
  - 2-D array pixels are NOT measured at the same time;
  - different rows in the detector array may see different tip/tilt (in the 1 10 seconds time frame);
  - need to remove the tip/tilt error from each row before construction of the phase map;

#### Our solution:

- dedicate 2 detectors as tip/tilt sensors;
- continuously measure the tip/tilt between the measurement and reference wavefronts;
- remove the tip/tilt error from each row measurement before constructing the surface map.

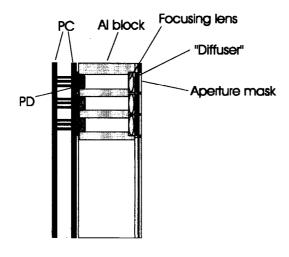
June 18, 1999

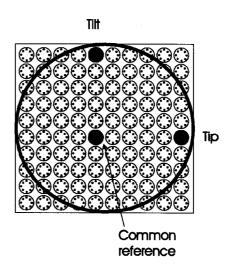


## **Detector Array**



- 10 X 10 detectors;
  - thermal deformation generally in low spatial frequency;
  - compatible with number of nodal points in thermal modeling of a surface;
- Si PIN photo-diode with low power dissipation amplifier;
- Reference to one common detector;
- Two detectors to measure tip/tilt (0.1-1Hz);
- Printed-circuit boards to align diodes and improve thermal conduction with a copper layer;
- "Diffuser" to achieve more uniform and more stable illumination on the photo-diode active region;
- Aperture positioning tolerance ~1μm.



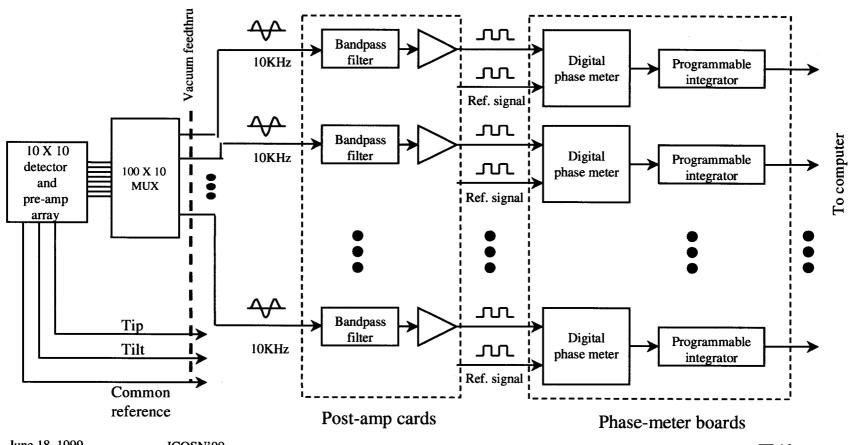






## DAQ Block Diagram

- Use modified version of current 1-D metrology electronics H/W and S/W;
- 100 X 10 MUX to handle 100 channels;
- 2 high precision phase-meter boards (total 12 channels, 2 used for tip/tilt);
- 2 tip/tilt channels are "on" all the time.



June 18, 1999

ICOSN'99

FZ-16

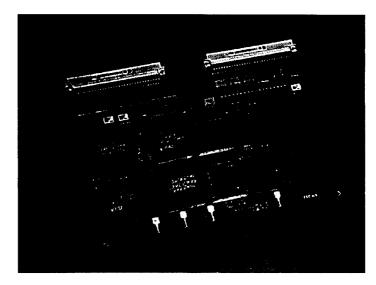




## Data Acquisition Electronics

- A 100 X 10 MUX board in vacuum to switch 10×10 channels sequentially (switching time < 100ms);
- $\sim 0.1$  mfringe instantaneous phase resolution, and 1  $\mu$ fringe for averaging over 1 sec;
  - optical power about  $1\mu W$  per channel at  $\lambda=532$ nm, fringe visibility  $\sim 0.5$ ;
  - carrier frequency (heterodyne frequency) is 10KHz;
- Stability of total delay (from where photoelectrons are generated to phase meter) <200 ps/hr between ref and unknown channels.

#### High Precision Phase-meter Board



June 18, 1999





## Summary

- Proposed COPHI concept for subnanometer surface metrology;
  - measurement of changes of surface figure and wavefront stability;
- Common-path reduces:
  - fringe phase error due to laser frequency and intensity fluctuations;
  - optical path length error caused by structural vibrations (piston mode).
- Integration and test under way;
- Broad potential applications:
  - thermal deformations of optics; beam walk (single mirror, compressor, delay line, etc.); corner cube articulation error; and on-board wavefront monitoring.